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(71) Applicant: **International Business Machines Corporation, Old Orchard Road, Armonk, N.Y. 10504 (US)**

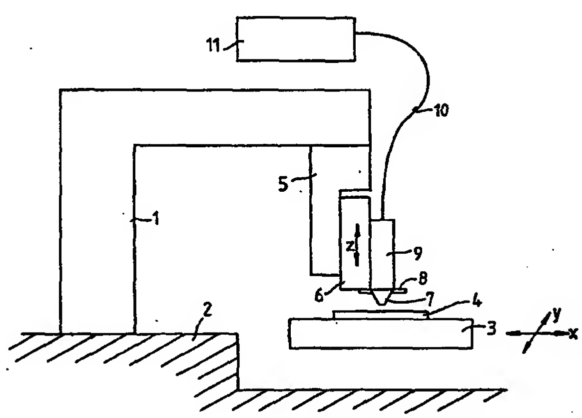
(72) Inventor: **Pohl, Dieter Wolfgang, Dr., Felsenhofstrasse 10, CH-8134 Adliswil (CH)**

(74) Representative: **Rudack, Günter O., Dipl.-Ing., Säumerstrasse 4, CH-8803 Rüschlikon (CH)**

(54) ***Optical near-field scanning microscope.***

(57) *The optical near-field scanning microscope comprises an «objective» (7) attached to the conventional vertical adjustment appliance (6) and consisting of an optically transparent crystal having a metal coating with an aperture at its tip with a diameter of less than one wavelength of the light used for illuminating the object (4). Connected to the aperture-far end of the «objective» (7) is a photodetector (11) via an optical filter (9) and an optical fiber glass cable (10). Scanning the object (4) is done by appropriately moving the support (3) along x/y-coordinates.*

The resolution obtainable with this microscope is about 10 times that of state-of-the-art microscopes.



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OPTICAL NEAR-FIELD SCANNING MICROSCOPE

This invention relates to optical microscopes in which an aperture is scanned across the object to be inspected, and wherein the light quanta received are processed electronically to improve the resolution power and depth of focus.

The term "near-field" is intended to express the fact that the aperture is located near the object at a distance smaller than the wavelength. The term aperture is used here to describe the pointed end of a light waveguide which forms an entrance pupil with a diameter of less than 1 μm.

Conventional scanning microscopes comprise essentially a focusing means to focus radiation from a light source onto an object to be inspected, a radiation detector, and scanning means to cause relative movement between the focus and the object.

The ultimate limit of resolution of state of the art optical devices, such as microscopes, is of the order of one wavelength, i.e. about 500 nm. Two neighbouring object points are considered to be just resolved if in the image the principal diffraction maximum of the first object point coincides with the first diffraction minimum of the second object point (Lord Rayleigh, Phil. Mag. (5), 8(1879)261).

The distance Y between two object points which an optical microscope can just resolve, when the illumination is incoherent and the microscope's aperture is circular, is $\sim 0{,}61\lambda/n \cdot \sin\Theta$, wherein the term

$n \cdot \sin\theta$ is the "numerical aperture", i.e. the product of the refractive index n and of the semi-angle θ of the cone of rays in the object space. The numerical aperture should be large if a high resolving power is to be achieved (M. Born and E. Wolf, Principles of Optics, Pergamon Press, London 1959, p. 417f). Considering that the largest numerical apertures so far achievable are about 1,3 ... 1,4, the best resolution is of the order of $0{,}5\lambda$.

The above-mentioned resolution limit is derived under the assumption that the optical instrument is based on imaging and implies that both the diameter 2a of the entrance pupil of the objective and its distance h from the object are large compared to the wavelength λ of the illumination used ($a, h \gg \lambda$). Because of the shortness of the wavelengths present in visible light compared with the smallest diameter to which an entrance pupil could be manufactured hitherto, this condition is satisfied in conventional optical instruments in a natural way.

Numerous attempts to increase the resolving power of microscopes are known from the prior art. In U.S. Patent 3,926,500 a diaphragm having small openings is rotated in a plane conjugate to the object plane. The object to be inspected is illuminated through the diaphragm such that light passing through its openings is sharply focussed only on areas lying in or near to the object plane within the depth of focus range of the objective. Accordingly, only light reflected from said areas can contribute to the formation of a clear image. When either the object or the diaphragm are cyclically shifted in the direction of the optical axis,

the depth of focus of the microscope can be somewhat extended, at the disadvantage, however, that the actual roughness of the surface inspected is equalled out.

According to the literature reference "Optische Abbildung unter Ueberschreitung der beugungsbedingten Auflösungsgrenze" by W. Lukosz and M. Marchand, Optica Acta 10 (1963) p. 241, the resolution of the optical system can be increased by a grid-like arrangement of the scanning diaphragm pinholes.

U.S. Patent 4,198,571 describes the improvement of the resolution of scanning microscopes through the use of an annular lens, which may be a circular lens with a closely spaced annular aperture. A disadvantage with such an arrangement is the severe loss of power through the annulus which requires the employ of a sufficiently powerful source of coherent light, such as a laser.

The references cited clearly indicate that efforts have been made to push the natural limitation given by the dimensions of the optical elements, particularly lenses, used in optical microscopes. None of the references proposes a microscope without imaging elements having a submicron optical aperture only.

The invention proposes an optical microscope which circumvents the resolution limit through the use of an aperture with an entrance pupil diameter 2a and a distance h from the object which are small compared to the wavelength. The aperture receives a signal the intensity of which depends on the transmissivity of a spot on the illuminated object right opposite its entrance

pupil. When scanned along the surface, the intensity varies according to the objective transmissivity. The record of the scan represents an "image" of the object. The resolution of the "image" can be substantially below the classical resolution limit, say $\lambda/10$.

Key element of such an optical microscope is, of course, the aperture, and the following specification will in part be devoted to a description of an aperture manufactured from a pyramid-shaped transparent crystal the apex of which has been machined to yield a radius of curvature equal to or less than the desired resolution.

A pyramid-shaped lens is known from the article "Self-Image and Enlarging Lens" by T.S. Fitzgerald in IBM Technical Disclosure Bulletin Vol. 18 (1976) p. 4174. This lens is used for enlarging an image recorded on photographic film (e.g. microfiche) and displaying it on its frosted base surface. A lens as disclosed in this reference, apart from having macroscopic dimensions, cannot be used in a microscope application as more is needed than just cutting the apex: provision must be made to precisely delineate the borders of the aperture, a measure not required in the macroscopic application shown in the reference.

The invention accordingly relates to an optical near-field scanning microscope comprising an aperture with arrangements for mutual scanning displacement between the aperture and the object to be viewed at a controllable distance therebetween, a photodetector optically connected to said aperture, and a light source. The characteristics of this microscope reside in the

fact that the aperture consists of a transparent body covered with an opaque layer into which an opening is formed the diameter of which is small compared to the wavelength of the light used for illuminating the object to be viewed. In a preferred embodiment, the microscope comprises a photodetector with an optical filter arranged between the aperture and said photodetector, in another embodiment, the light source is arranged to illuminate the specimen through the aperture while the transmitted or reflected light is collected by a sensor outside of the aperture.

Details of embodiments of the invention will be explained by way of example in the following description and with reference to the drawings in which:

Fig. 1 is one embodiment of the scanning microscope in accordance with the invention;

Fig. 2 is another, "inverse" embodiment of the scanning microscope;

Fig. 3 is a grossly enlarged view of the aperture used in the microscopes of Figs. 1 and 2;

Fig. 4 is a diagram showing schematically the intensity decrease of the light passing the opaque layer of the aperture of Fig. 3;

Fig. 5 is a diagram comparing the resolutions of various types of microscopes.

Fig. 1 shows the general disposition in a first embodiment of the elements of a near-field optical scanning microscope in accordance with the present in-

vention. For the purposes of explanation all elements have been drawn without regard to their actual proportions. A frame 1 is secured to a bench 2 which in a conventional fashion also carries a support 3 arranged for x/y-movement by conventional means not shown. Support 3, which may be transparent and transilluminated from below, carries the object 4 to be inspected. Frame 1 has an arm 5 extending therefrom and carrying a vertical adjustment appliance 6 for adjusting the distance of an aperture 7 from object 4, the distance being controlled by means of a sensor 8 and conventional adjustment means not shown. Attached to aperture 7 is an optical filter 9 which in turn is connected via a light guide 10 to a photodetector 11 which may comprise a photomultiplier or the like. Filter 9 is not essential but helps to discriminate against unwanted radiation.

Scanning displacement between aperture 7 and the object 4 to be viewed may easily be achieved by moving support 3 with respect to bench 2 and, hence, aperture 7, with the aid of piezo-electric translators known to elongate or contract in response to appropriate voltages applied to electrodes attached to opposite surfaces thereof. Since the elongations/contractions of these crystals are proportional to the potential applied, reproducible displacements smaller than micrometers can be achieved.

The vertical adjustment of the aperture is preferably divided into the conventional coarse and fine adjustments, whereby the coarse adjustment may be made by means of a rack-and-pinion assembly, whereas for fine adjustment another piezo-electric translator may be used.

When scanned along the surface, the light transmitted through the aperture varies in accordance with the light intensity transmitted by the object. The resolution to be achieved is approximately h+a. The distance h favorably is $\leq 2a$, hence 2×20 nm $\triangleq \lambda/10$.

In an alternative embodiment which may be regarded as an inversion of the first embodiment just described, and which is shown in Fig. 2, illumination of the object 4 to be inspected is provided through the aperture 7 which may be associated with or integrated into an appropriate light source 12 which may comprise, e.g. a semiconductor laser known in the art. Light reflected from object 4 is controlled by one or more sensors 13 arranged in juxtaposition to object 4. Obviously, this inverted configuration has similar properties as the first described embodiment but may be more advantageous under certain circumstances. In particular, the intensity of light at the object can be considerably lower in this case.

Alternatively, the inverted arrangement can be used in transmission by placing a detector under the sample.

As mentioned before, the critical element of the microscope in accordance with the present invention is the aperture 7. Fig. 3 shows the lower end of optical filter 9 to which a pyramid-shaped transparent crystal 14 is connected. Optical filter 9 may, e.g. have a cross section of about 200x200 µm, while crystal 14 is selected to have a very sharp apex 15 formed by the facets 16 thereof with a radius of curvature r_c equal to, or

less than, the desired resolution, which for the purposes of explanation is assumed to be in the 20 nm range.

Crystal 14 has a metal coating 17 (not drawn to scale) with a typical thickness of about 200 nm. This is considered thick enough to be practically opaque. At the apex 15 the tip 18 of the crystal 14 and the metal film 17 are removed (e.g. by ion milling) so as to expose crystal 14 over an essentially square area 19 having a side length a of less than 100 nm, for example 20 nm. Area 19 is transparent to light and is used as the entrance pupil of the microscope. Very close to area 19, metal coating 17 is thinner than 200 nm in the direction of the optical axis and thus will have some transmissivity which will, however, quickly decrease with distance from the optical axis as schematically shown in the diagram of Fig. 4. The penetration depth of light into metal being approximately 12 nm for a reasonably good reflector (like Al), the effective aperture will be slightly larger than a^2. During the fabrication of the aperture, the transmission of light is monitored so that the ion milling (or other) process might be stopped when the entrance pupil has reached the desired size.

An alternative to the aperture produced from a crystal is one made of an optical glass fiber. A monomode glass fiber consists of a core with a diameter on the order of magnitude of the wavelength of the light to be transmitted, and of a cladding surrounding the core and having a lower refractive index than the core, such that total reflection can occur within the latter. For the purposes of the microscope under description, a glass fiber may be coated at one plane end with an opa-

que coating, such as metal, and a coaxial hole drilled into the coating (e.g. with an electron beam) so as to just expose the core. With an optical fiber prepared as described above an aperture is obtained which has essentially the same characteristics as an aperture produced from a pyramid-shaped crystal.

Although small with respect to the wavelength λ, the entrance pupil has a finite transmission. A semi-quantitative estimate is possible from the theory of Mie Scattering in combination with Babinet's theorem, according to which the transmission is approximately equal to the reflection of a conducting sphere. The transmissivity of an opening with the radius a ($a < \lambda$) is $T_a = 4/3 \cdot (2\pi\ a/\lambda)^4$ and the "transmission cross section" is $Q_a = a^2 \pi \cdot T_a$. Assuming a radius of 20 nm and a wavelength λ of 500 nm, $T_a \sim 0{,}5\%$ and $Q_a \sim 6{,}7 \cdot 10^{-14}$ cm^2. The flux through the aperture is $\phi_a = Q_a\ I^{(i)}$ and is $\phi_a = 6\ 10^{-13}$W, if a rather conservative value of $\phi = 10$W/cm^2 for the incident radiation is employed. This corresponds to $2 \cdot 10^6$ photons/s which is an easily detectable amount for present-day photo multipliers. In view of the a^6-proportionality of the transmission cross section Q_a, halving the radius a would lead to a flux of $3 \cdot 10^3$ photons/s only.

In view of the possible roughness of the object surface, the distance of the aperture from the surface has to be monitored with high resolution. Various techniques may be used for this purpose:

1) Mechanical scanning with a conventional "Talystep" apparatus having a heigh resolution of ~5 nm.

2) Differential interference contrast microscopy (Nomarski method) with a <1 nm resolution.

3) Frustrated total internal reflection: An evanescent wave decays exponentially in the space above the object, providing a sensitive measure of distance from the object surface. The sensor could be either the aperture itself or a separate, preferably larger sensing element.

4) Measurement of the capacitance between the aperture (metallized surface) and the object or the support.

With working distances in the 10...50 nm range, a resolution of ~1 nm is possible. While technique 1) above is considered marginal, techniques 2) and 4) will certainly, and technique 3) will probably provide the required resolution.

Mutual displacement along x/y-coordinates between object 4 and aperture 7 can be achieved e.g. by moving support 3 in a stepwise fashion. A useful travelling support is described in European Patent Publication No. (Patent Application 81 106 229.8) "Electric Travelling Support which Permits Displacements in the Nanometer Range".

A comparison of the scanning near-field optical microscope according to the present invention with conventional microscopes shows that it exceeds optical microscopes by a factor of 5 or better in resolution, but does not achieve the resolution of electron microscopes. In favorable contrast to these, it can be operated in air or liquids like conventional optical

instruments. It also provides optical spectral information. Accordingly, the microscope of the present invention is well suited for application in the following fields: Microelectronics, surface sciences, thin film technology, biology, etc. In Fig. 5, the lateral and vertical resolution of the scanning near-field optical microscope (20) is compared with that of the human eye (21), conventional optical microscopes (22), electron microscopes (23) and the recently developed scanneling tunneling microscope (24) as disclosed in U.S. Patent 4,343,993.

C L A I M S

1. Optical near-field scanning microscope comprising an aperture with arrangements for mutual scanning displacement between the aperture and the object to be viewed at a controllable distance therebetween, a photodetector optically connected to said aperture, and a light source, characterized in that the aperture (7) consists of a transparent body (14) covered with an opaque layer (17) into which an opening (19) is formed the diameter of which is small compared to the wavelength of the light used for illuminating the object (4) to be viewed.

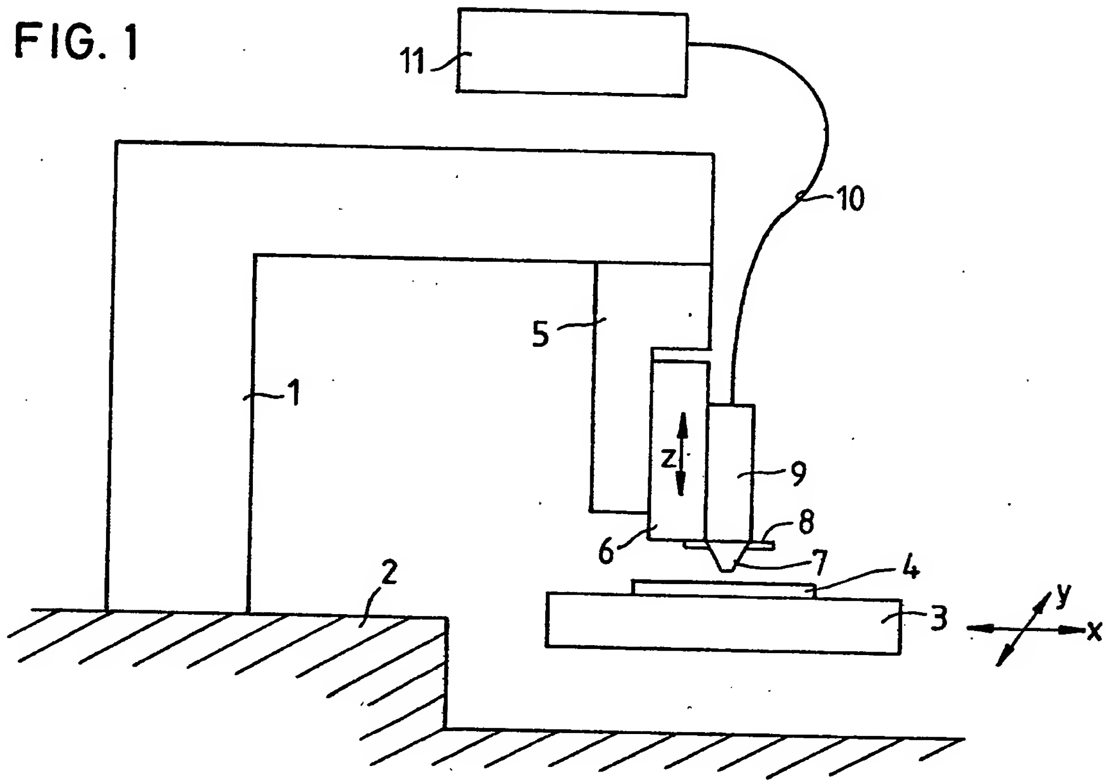
2. Microscope according to claim 1, characterized in that the aperture (7) consists of a pyramid-shaped transparent crystal (14) with its triangular facets (16) covered with an opaque metal layer (17) which at the apex (15) of the crystal (14) is removed so as to form a pupil (19) of between 10 and 500 nm side length of the crystal (14).

3. Microscope according to claim 1, characterized in that the objective (7) consists of an optical glass fiber the cladding at the tip of which has partially been replaced by an essentially opaque coating having a hole of between 10 and 500 nm diameter centered with the axis of the core of said glass fiber.

4. Microscope according to any one of claims 1 through 3, characterized in that the aperture (7) is mounted on a holder (6) for mutual displacement

with respect to the object (4) at a controlled distance smaller than the optical wavelength of the light illuminating the object (4).

FIG. 1



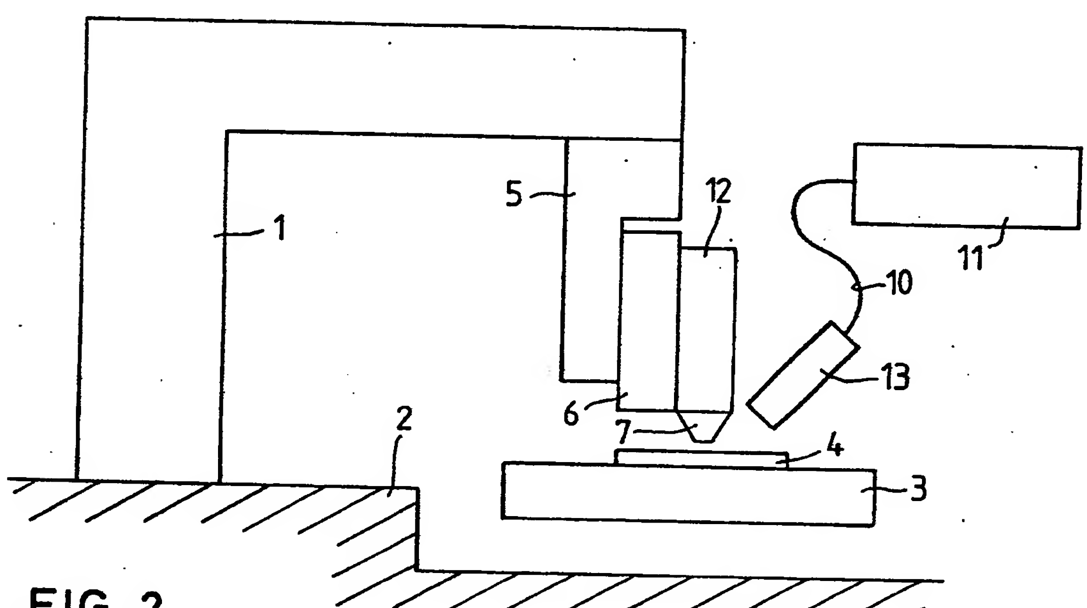
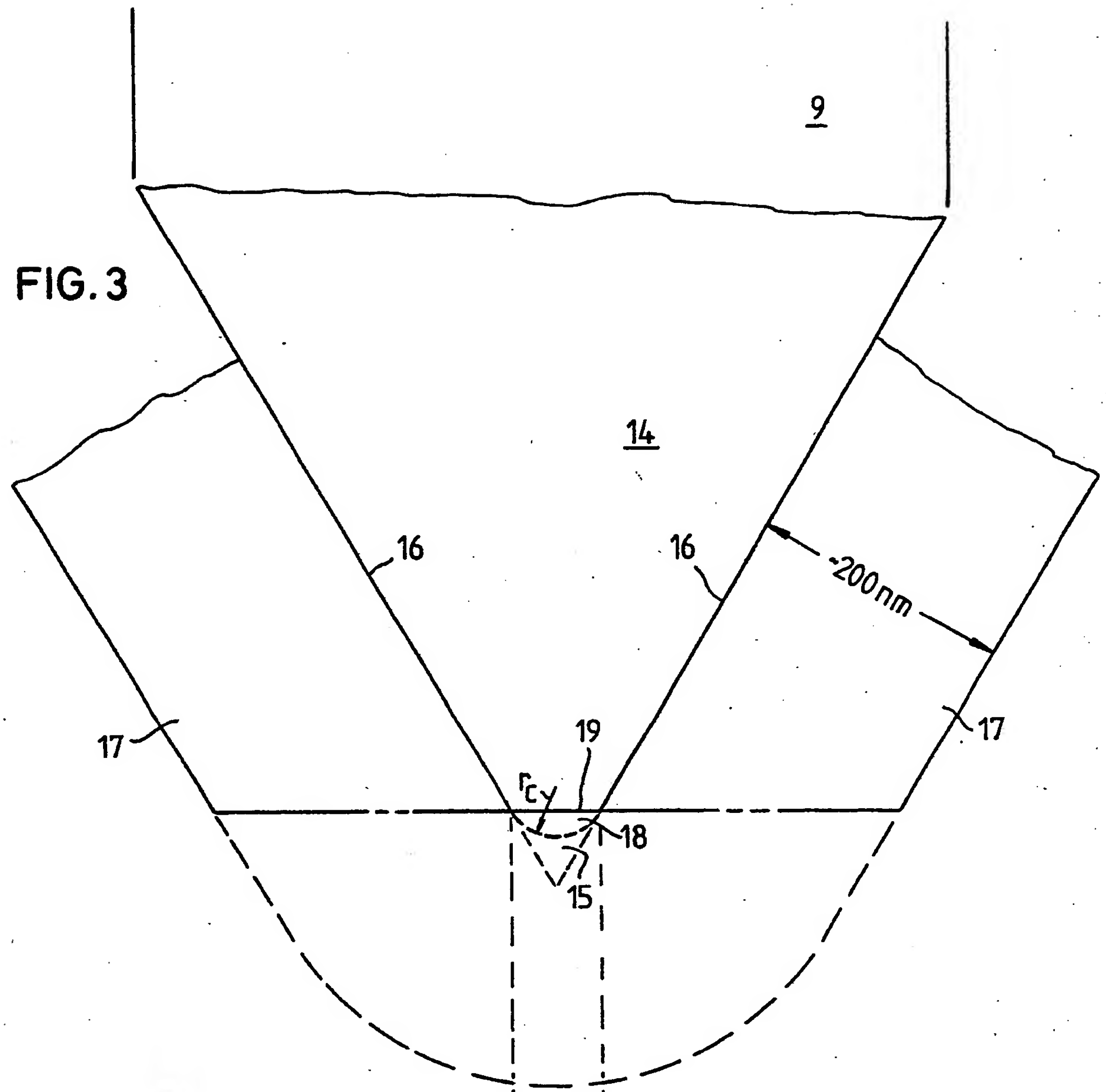


FIG. 2

FIG. 3



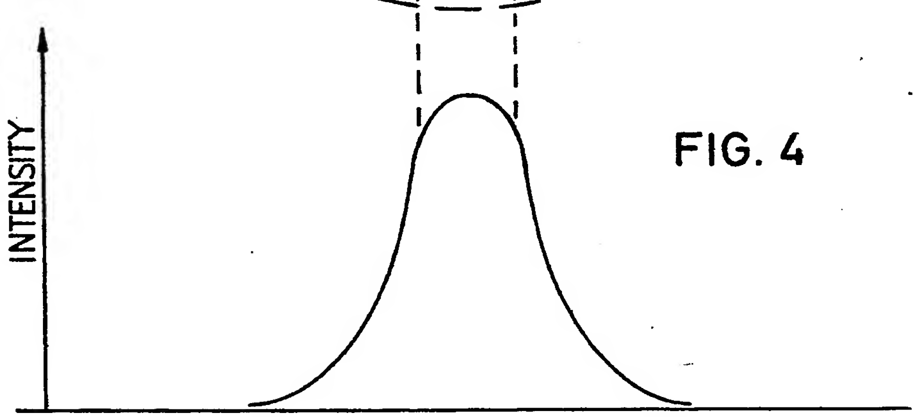
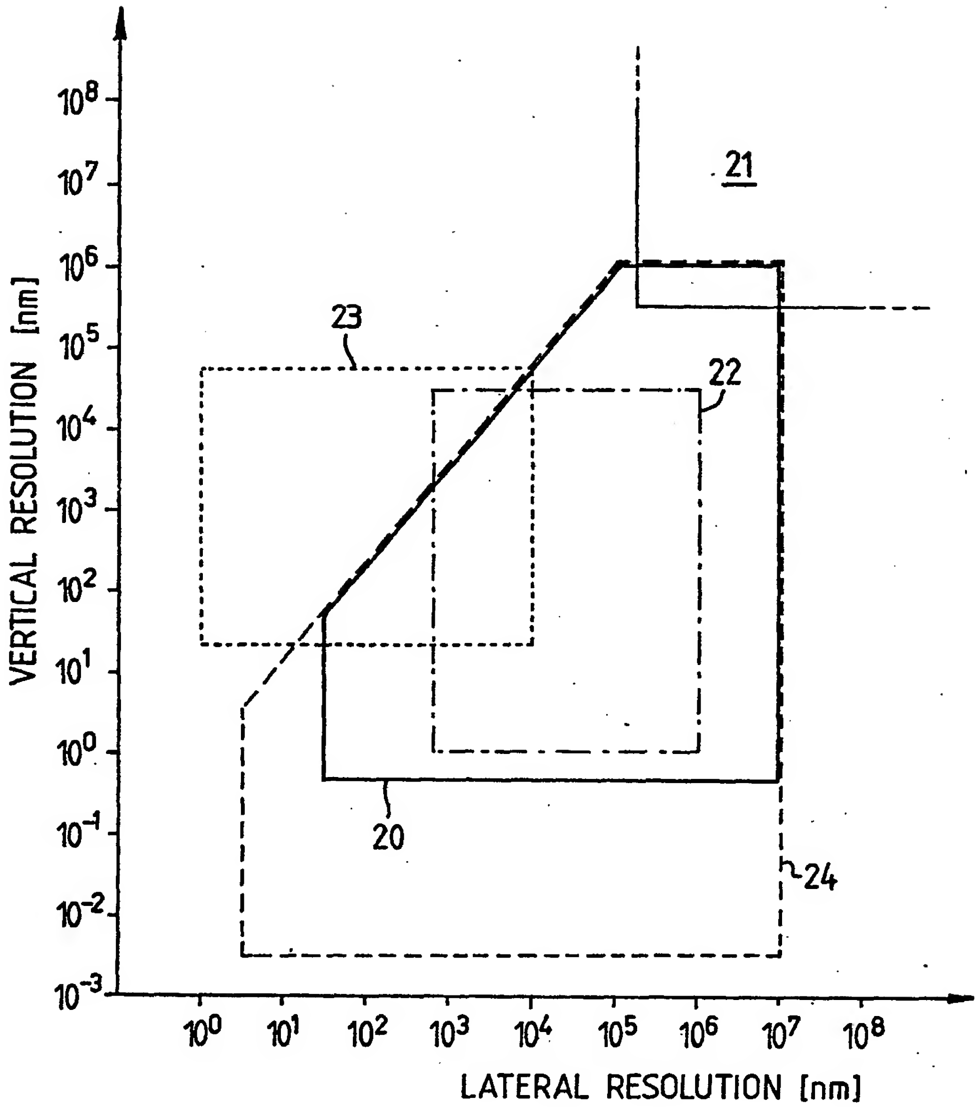


FIG. 4

FIG. 5



VERTICAL RESOLUTION [nm]
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
21
23
22
20
24
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
LATERAL RESOLUTION [nm]

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EUROPEAN SEARCH REPORT

0112401

Application number

EP 82 11 1974

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl. 3)
Y	US-A-3 187 627 (N.S. KAPANY) * Column 5; claim 1 *	1,3	G 02 B 21/00 G 02 B 5/16
Y	US-A-4 240 692 (R. WINSTON) * Claim 13 *	1,3	
A	DE-A-1 232 367 (DATA CORP.) * Claim 1; column 3, lines 14-18 *	1	
A	US-A-3 705 755 (S.C. BAER) * Claim 1 *	1	
D,A	IBM TECHNICAL DISCLOSURE BULLETIN, vol. 18, no. 12, 1976, page 4174	2	TECHNICAL FIELDS SEARCHED (Int. Cl. 3)
A	EP-A-0 052 892 (HITACHI LTD.) * Figure 1 *	4	G 02 B 5/16 G 02 B 21/00 G 02 B 27/17 G 02 B 27/58
A	US-A-3 497 694 (S. JURA et al.) * Figure 1 *	4	

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
BERLIN	06-05-1983	FUCHS R

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alon
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